Impact of an unusually large warm-core eddy on distributions of nutrients and phytoplankton in the southwestern Canada Basin during late summer/early fall 2010

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[1] Recent freshening of the Arctic Ocean due to melting of sea ice and enhanced Ekman pumping has deepened the nutricline over the Canada Basin and reduced nutrient concentrations in the euphotic zone. Cold-core eddies frequently transport nutrient-rich shelf water to the Canada Basin, but the eddies are much deeper than the euphotic zone. Because warm-core eddies appear near the surface or at a depth range shallower than that of the cold-core eddies, they may play a crucial role in determining nutrient distributions in the euphotic zone and hence may affect primary production. During late summer/early fall 2010, we conducted detailed surveys of a warm-core eddy, which was unusually large (~100 km in diameter). We suggest that this warm-core eddy which contained high-ammonium shelf water could supply ammonium to the euphotic zone in the southwestern Canada Basin and may sustain ~30% higher biomass of picophytoplankton (<2 μm) than that in the surrounding water in the basin. The role of warm-core eddies in supplying nutrients to the euphotic zone and controlling phytoplankton distributions seems to be more important than previously because the recent deepening of the nutricline in the Canada Basin has decreased the nutrient supply to the euphotic zone. **Citation:** Nishino, S., M. Itoh, Y. Kawaguchi, T. Kikuchi, and M. Aoyama (2011), Impact of an unusually large warm-core eddy on distributions of nutrients and phytoplankton in the southwestern Canada Basin during late summer/early fall 2010, *Geophys. Res. Lett.*, *38*, L16602, doi:10.1029/2011GL047885.

1. Introduction

[2] Mesoscale eddies are ubiquitous in the world's oceans. They bring episodic pulses of nutrients into the euphotic zone and can thus affect primary production [*Falkowski et al.*, 1991; *Benitez-Nelson et al.*, 2007]. The Canada Basin of the Arctic Ocean includes a large number of eddies with diameters of 10–20 km, which are predominantly anticyclonic [*Manley and Hunkins*, 1985]. Three types of eddies have been characterized in the southern Canada Basin from hydrographic and mooring observations [*Pickart and Stossmeister*, 2008]: subsurface anticyclonic cold-core (100–200 m) and warm-core (50–100 m) eddies and surface-intensified warm-core (0–50 m) eddies. The subsurface eddies are likely formed by the hydrodynamic instability of a shelf-break jet along the northern edge of the Chukchi Sea shelf [*Pickart et al.*, 2005; *Spall et al.*, 2008]. The subsurface cold-core eddies are spawned from the shelf-break jet during spring and early summer when the jet is advecting Pacific Winter Water (PWW) that has passed over the Chukchi Sea shelf during winter. The subsurface warm-core eddies are formed later in the year into the fall when the shelf-break jet has been replaced with Pacific Summer Water (PSW), which is warmer summertime Chukchi Sea shelf water [*Pickart and Stossmeister*, 2008]. The surface-intensified warm-core eddies are often observed in the vicinity of Barrow Canyon [*D'Asaro*, 1988]. Using an eddy-resolving model, *Watanabe and Hasumi* [2009] suggested that the eddies are generated as a result of the instability of a jet of Alaskan Coastal Water (ACW) through Barrow Canyon during August to October.

[3] The most commonly observed type of eddy in the southern Canada Basin is the subsurface cold-core anticyclone [*Pickart and Stossmeister*, 2008]. Because the cold-core eddy contains nutrient-rich PWW, it plays an important role in the transport of nutrients from the Chukchi Sea shelf to the Canada Basin [*Muench et al.*, 2000; *Mathis et al.*, 2007]. The eddies are typically 20 km in diameter and 75 m in thickness, and assuming that 125 eddies are formed each year with nitrate, silicate, and phosphate concentrations of 18.0, 53.1, and 2.2 μmol/L, respectively, they carry 5.63×10^{10} moles-nitrate year^{-1}, 1.56×10^{11} moles-silicate year^{-1}, and 6.88×10^{9} moles-phosphate year^{-1} from the Chukchi Sea shelf to the Canada Basin, which could maintain the nutrient maxima in the basin [*Mathis et al.*, 2007]. However, the depth of the nutrient maxima (~150–250 m) is much deeper than the euphotic zone (~50 m) in the Canada Basin, and therefore the nutrients carried by the cold-core eddies would be hardly used for primary production.

[4] It seems likely that the warm-core eddies would also transport nutrients from the Chukchi Sea shelf to the Canada Basin [*Mathis et al.*, 2007]. Because the warm-core eddies appear near the surface or at a depth range shallower than that of the cold-core eddies [*Pickart and Stossmeister*, 2008], they may play a crucial role in controlling nutrient distributions in the euphotic zone and hence may affect primary production. Although warm-core eddies have sometimes been found in hydrographic sections and satellite images [*D'Asaro*, 1988; *Pickart and Stossmeister*, 2008], and their formation mechanism has been investigated to some extent [*Pickart et al.*, 2005; *Spall et al.*, 2008; *Watanabe and Hasumi*, 2009], few studies have examined their influences on nutrient distributions and biological activities due to the lack of chemical and biological data from such features.

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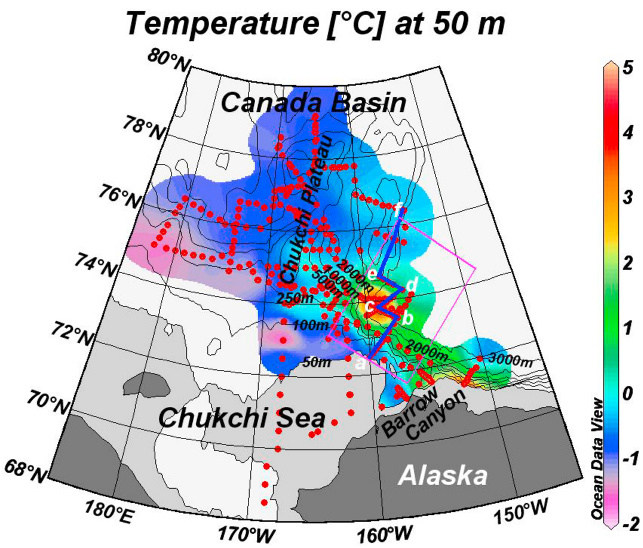

Figure 1. Hydrographic stations of CTD/water sampling and XCTD (red dots) of the R/V *Mirai* Arctic Ocean cruise in 2010 and temperature distribution at 50 m depth (color). Contour lines indicate isobaths of 50, 100, 250, 500, 1000, 2000, and 3000 m. The blue lines indicate the locations of the vertical sections illustrated in Figures 2 and 3. The apexes of the blue lines are denoted *a*, *b*, *c*, *d*, *e*, and *f* from south to north, and their locations in the vertical sections of Figure 2b and Figure 3c are indicated by the same letters. Data within the pink square area obtained from the R/V *Mirai* Arctic Ocean cruises in 2002 and 2004 are used for the illustration of vertical sections in Figure 4.

[5] In late summer/early fall 2010, we found an anticyclonic warm-core eddy north of the Chukchi Sea shelf slope in the southwestern Canada Basin (Figure 1). The eddy was approximately 100 km in diameter, which is unusually large compared with previously reported diameters of 10–20 km [*Manley and Hunkins*, 1985; *D'Asaro*, 1988; *Muench et al.*, 2000; *Pickart and Stossmeister*, 2008]. Detailed hydrographic surveys were conducted on this large warm-core eddy with high-horizontal-resolution, physical and chemical sampling, and lower-horizontal-resolution biological sampling. Here, we describe the observed characteristics of the warm-core eddy and suggest that it affects nutrient distributions, which might be favorable for picophytoplankton (<2 μm cell size) production in the southwestern Canada Basin.

2. Data and Methods

[6] We conducted hydrographic observations in the western Arctic Ocean in late summer/early fall 2010 (2 September–16 October) on board the R/V *Mirai* of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). A conductivity-temperature-depth system (CTD; Sea-Bird Electronics Inc., SBE9plus) and a carousel water sampling system with 36 Niskin bottles (12 L) were used for the observations. A sensor of photosynthetically active radiation (PAR) was attached to the CTD, and the depth of the euphotic zone was estimated as the depth at which PAR was 1% of its surface value. Seawater samples were collected for measurements of salinity, dissolved oxygen, nutrients (nitrate, nitrite, phosphate, silicate, and ammonium), total and size-fractionated chlorophyll *a*, and other chemical and biological parameters. In this study, we used the nutrient and chlorophyll *a* data from the seawater samples. Nutrient samples were analyzed according to "The GO-SHIP Repeat Hydrography Manual [*Hydes et al.*, 2010]" using the Reference Materials of Nutrients in Seawater [*Aoyama and Hydes*, 2010; *Sato et al.*, 2010]. Chlorophyll *a* in the seawater samples was measured using a fluorometric non-acidification method [*Welschmeyer*, 1994] and a Turner Design fluorometer (10-AU-005). For size-fractionated chlorophyll *a* measurements, phytoplankton cells were fractionated using three types of nucleopore filters (pore sizes: 10, 5, and 2 μm) and a Whatman GF/F filter (pore size: ~0.7 μm). Expendable CTD (XCTD) probes were also launched between CTD stations. General descriptions of the 2010 R/V *Mirai* cruise were provided in the cruise report, and the data will be open to the public via the JAMSTEC data website (http://www.godac.jamstec.go.jp/cruisedata/mirai/e/index.html).

[7] For comparison with previous years, we also used R/V *Mirai* data obtained in late summer/early fall 2002 (24 August–10 October) and 2004 (1 September–13 October). The cruise reports and the data are already open to the public via the JAMSTEC data website (http://www.godac.jamstec.go.jp/cruisedata/mirai/e/index.html).

3. Results

[8] Vertical sections of the warm-core eddy observed in 2010 are shown in Figure 2. Warm water was found north of the Chukchi Sea shelf slope (around 200 km in the hori-

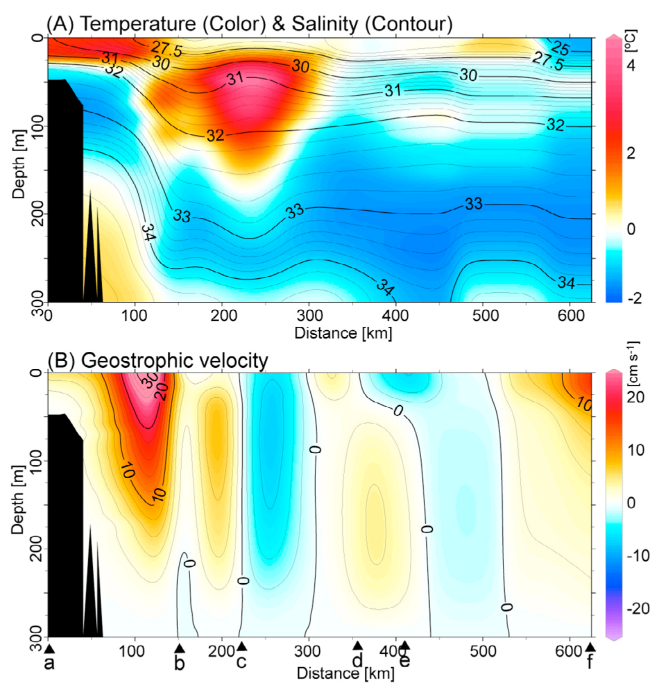

Figure 2. Vertical sections of (a) temperature [°C] (color) and salinity (contours) and (b) geostrophic velocity [cm/s] from the Chukchi Sea shelf to the Canada Basin along the blue lines illustrated in Figure 1. The locations represented by letters *a*, *b*, *c*, *d*, *e*, and *f* in Figure 2b correspond to the locations of apexes of the blue lines labeled with the same letters in Figure 1. Geostrophic velocity was calculated assuming the level of no motion lies at 300 db. Data were obtained from the R/V *Mirai* Arctic Ocean cruise in 2010.

zontal axis of Figure 2a) near the surface to a depth of 150 m. The core temperature reached 5°C, and thus the warm water would have been derived from the ACW [*Coachman et al.*, 1975]. The geostrophic velocity indicated that the warm water was spinning anticyclonically and that the eddy was located north of a strong westward flow over the shelf slope (Figure 2b). Below the warm water, cold water occupied the area having salinity (S) of 33 and 34, and this water was identified as PWW. North of the warm-core eddy, some weak temperature maxima were found: a near-surface temperature maximum [*Jackson et al.*, 2010] and PSW (S = 31–32). Below the temperature maxima, there was a prominent and thick temperature minimum centered on $S \sim 33$, which is typical of PWW. On the other hand, the thickness of the temperature minimum below the warm-core eddy was very small, suggesting that the eddy could transport the warm water (ACW) to a depth corresponding to the upper boundary of the PWW. The diameter of the warm-core eddy was approximately 100 km, which is much larger than the scale of typical eddies (10–20 km). At present, we do not know why the eddy was so large, but a numerical model [*Watanabe and Hasumi*, 2009] suggested that the warm-core eddy could have increased in scale by merging with other warm-core eddies.

[9] The warm-core eddy was also characterized by high ammonium concentrations compared with the surrounding water at the same depths in the Canada Basin (Figure 3a). In the warm-core eddy, the depth where the ammonium concentration increased rapidly with depth (ammonium nutricline; ~30 m) was shallower than the euphotic zone depth (~50 m). In other words, the warm-core eddy could supply ammonium to the euphotic zone in the southwestern Canada Basin. North of the warm-core eddy, the ammonium concentration in the euphotic zone was almost zero. The high ammonium water in the eddy was found to a depth of 200 m, corresponding to the upper boundary of the PWW. This is consistent with the thinning of the temperature minimum in the eddy area, i.e., the warm-core eddy with high ammonium concentrations could penetrate to the PWW layer. In contrast to the ammonium nutricline, the anticyclone depressed the nitrate nutricline, i.e., the nitracline, the layer where the nitrate concentration increased rapidly with depth (Figure 3b). As a result, the nitracline in the eddy (~80 m) was much deeper than the euphotic zone (~50 m). North of the warm-core eddy, the nitracline was also deeper than the euphotic zone. In recent years, the nitracline in the Canada Basin has been deepening due to significant sea ice melting and enhanced Ekman pumping, resulting in freshwater accumulation in the surface layer, including the euphotic zone [*McLaughlin and Carmack*, 2010]. The deepened nitracline largely inhibits nitrate supply to the euphotic zone in the Canada Basin. Below the nitracline, the warm-core eddy contained low-nitrate water compared with the surrounding water in the Canada Basin. The low-nitrate water in the eddy seemed to negatively affect the nitrate-maximum layer, reducing its maximum concentration. The silicate and phosphate distributions (not shown) were similar to those of nitrates. The warm-core eddy contained low-silicate and low-phosphate water compared with the surrounding water in the basin.

[10] Phytoplankton distributions may also be affected by the warm-core eddy. The chlorophyll *a* concentration was extremely high in the shelf area and was even higher over the warm-core eddy compared with the water north of the eddy (Figure 3c). However, the composition of size-fractionated chlorophyll *a* differed dramatically between the shelf area and the warm-core eddy area. The phytoplankton biomass of cells >10 μm, 2–10 μm, and <2 μm in the top 50 m layer (approximately the euphotic zone) is shown in Figure 3d. The biomass of large phytoplankton (>10 μm) sharply decreased from the shelf area to the eddy area (Figure 3d; blue bars). The biomass of 2–10 μm phytoplankton was almost constant except for in the shelf area, where the biomass was slightly higher than in the basin (Figure 3d; green bars). Conversely, the biomass of picophytoplankton (<2 μm) was highest over the warm-core eddy (Figure 3d; red bars), where the biomass (7.2 ± 0.6 mg/m^2) was ~30% higher than that in the water north of the eddy (5.4±0.2 mg/m^2). In the shelf area, large phytoplankton dominated, whereas picophytoplankton dominated in the basin. The high chlorophyll *a* concentration and the predominance of large phytoplankton in the shelf area are explained by the high concentrations of nutrients in the euphotic zone. The predominance of picophytoplankton in the basin is consistent with the low nutrient concentrations in the euphotic zone. The higher biomass of picophytoplankton in the eddy area compared with the water north of the eddy may be sustained by the ammonium supplied to the euphotic zone by the warm-core eddy. The ammonium concentration in the euphotic zone was also high in the shelf area, but the biomass of picophytoplankton was low compared with that in the eddy area. In the shelf area, large phytoplankton such as diatoms were predominant. Diatoms are able to take up and store nutrients at a more rapid rate than picophytoplankton [*Smetacek*, 1998]. Therefore, the shelf would be an unfavorable place for picophytoplankton, even if the ammonium concentrations were high.

4. Discussion

[11] We found an anticyclonic warm-core eddy in the southwestern Canada Basin that contained ACW with high-ammonium but low-nitrate, low-silicate, and low-phosphate concentrations (Figures 3a and 3b). The nitrate, silicate, and phosphate concentrations of ACW (and PSW) are lower than those of PWW because of the nutrient consumptions of primary producers during summer over the Chukchi Sea shelf [*Walsh et al.*, 1989]. However, ammonium is produced during summer by the decomposition of organisms deposited at the bottom of the Chukchi Sea shelf [*Cooper et al.*, 1997; *Nishino et al.*, 2005]. Therefore, the ACW (and PSW) would have high ammonium concentrations but low levels of other nutrients. The spreading of ACW into the southwestern Canada Basin by the warm-core eddy could supply ammonium to the euphotic zone in the basin and may sustain ~30% higher biomass of picophytoplankton (<2 μm) than that in the surrounding water in the basin. Recently, the nitracline in the Canada Basin has been deepening [*McLaughlin and Carmack*, 2010], and the nitracline was deeper than the euphotic zone in 2010, resulting in an inhibition of nitrate supply to the euphotic zone. Therefore, the nitrogenous nutrient supply to the euphotic zone in the basin through ammonium transport by warm-core eddies would be more important than before.

[12] The distribution of ammonium in the Canada Basin differs each year and may be related to the accumulation of freshwater in the Canada Basin. In 2002, high-ammonium water seemed to spread from the Chukchi Sea shelf into

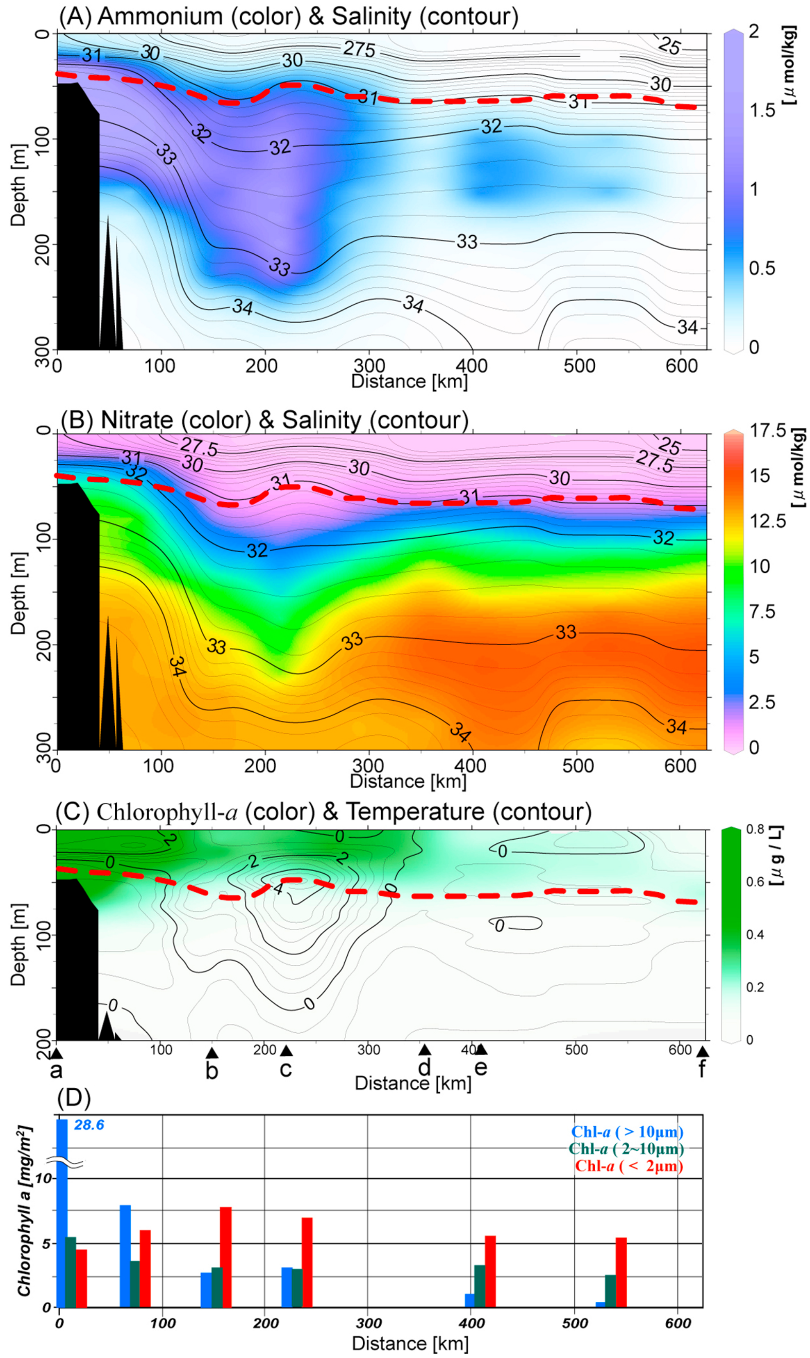

Figure 3. Vertical sections of (a) ammonium concentration [μmol/kg] (color), salinity (black contours), and euphotic zone depth (red-dashed contour); (b) nitrate concentration [μmol/kg] (color), salinity (black contours), and euphotic zone depth (red-dashed contour); (c) chlorophyll *a* concentration [μg/L] (color), temperature [°C] (black contours), and euphotic zone depth (red-dashed contour); and (d) phytoplankton biomass [mg/m^2] integrated over the water column from the surface to a depth of 50 m (approximately the euphotic zone) for phytoplankton chlorophyll *a* in cells >10 μm (blue bars), cells 2–10 μm (green bars), and cells <2 μm (red bars) from the Chukchi Sea shelf to the Canada Basin along the blue lines illustrated in Figure 1. The locations represented by letters *a*, *b*, *c*, *d*, *e*, and *f* in Figure 3c correspond to the locations of apexes of the blue lines labeled with the same letters in Figure 1. The euphotic zone depth was estimated as the depth where PAR is 1% of its surface value. Data were obtained from the R/V *Mirai* Arctic Ocean cruise in 2010.

the Canada Basin, and the ammonium concentration was reduced to almost zero distant from the shelf due to nitrification (Figure 4a). However, in 2004, the high-ammonium water was likely confined to a region near the shelf (Figure 4c). This confinement would have resulted from an inhibition of the spreading of shelf waters. The westward velocity over the shelf slope (along-slope velocity) was greater in 2004 (Figure 4d) than in 2002 (Figure 4b). The enhancement of along-slope flow is geostrophically associated with an increase in the gradient of isohaline (isopycnal)

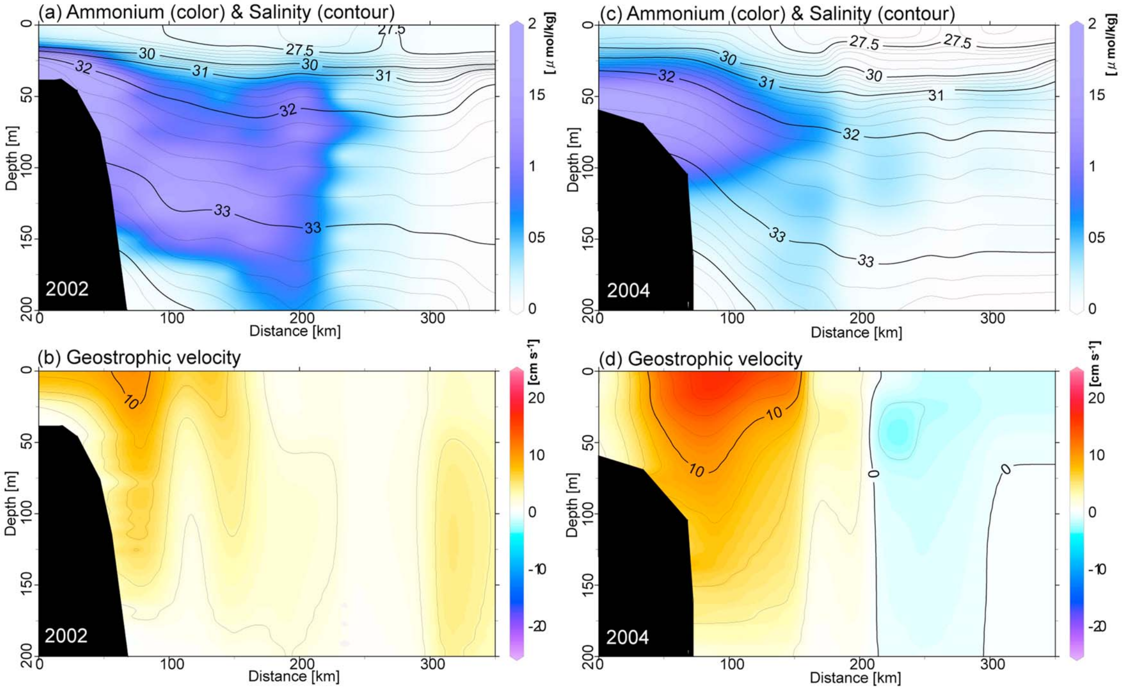

Figure 4. Vertical sections of (a) ammonium concentration [μmol/kg] (color) and salinity (contours) in 2002; (b) geostrophic velocity [cm/s] in 2002; (c) ammonium concentration [μmol/kg] (color) and salinity (contours) in 2004; and (d) geostrophic velocity [cm/s] in 2004 from the Chukchi Sea shelf to the Canada Basin within the pink square area in Figure 1. Geostrophic velocity was calculated assuming the level of no motion lies at 300 db. Data were obtained from the R/V *Mirai* Arctic Ocean cruises in 2002 and 2004.

surfaces over the shelf slope. The increase in the salinity gradient was caused by the accumulation of freshwater in the Canada Basin due to sea ice melting and enhanced Ekman pumping in the basin [*McLaughlin and Carmack*, 2010; *Nishino et al.*, 2011]. Although cross-slope currents with large spatial and temporal variability could spread the high-ammonium shelf water toward the Canada Basin in both years, the stronger westward along-slope flow in 2004 was more effective at inhibiting the cross-slope spread. As a result, the high-ammonium water was confined to the shelf side of the strong westward flow in 2004. The westward flow over the shelf slope was much stronger in 2010 (Figure 2b) because of the accelerated freshwater accumulation in the Canada Basin since 2007 [*McLaughlin and Carmack*, 2010]. However, in 2010 we found relatively high ammonium water north of the strong westward flow, which was carried by the warm-core eddy as described above (Figure 3a).

[13] In 2010, the afore-mentioned warm-core eddy was probably a major ammonium provider to the Canada Basin. An eddy containing relatively high-ammonium water with an average concentration of 0.9 μmol/L, a diameter of 100 km, and a depth of 50–200 m (150 m thick) would transport 1.06×10^9 moles ammonium to the ammonium-free Canada Basin. It would be informative to compare nutrient supply to the basin by the warm-core eddy with that of a cold-core eddy. *Mathis et al.* [2007] suggested that a typical cold-core eddy with a diameter of 20 km and a thickness of 75 m contains PWW, which has a nitrate concentration that is 5 μmol/L higher than that in the Canada Basin, and hence carries 1.25×10^8 moles excess nitrate to the Canada Basin. Therefore, from the viewpoint of the eddy's impact on nitrogenous nutrient distribution in the Canada Basin, the warm-core eddy in this study carried 8.5 times more excess nitrogenous nutrient than a typical cold-core eddy. However, more than 100 cold-core eddies are produced a year [*Manley and Hunkins*, 1985; *Mathis et al.*, 2007], but the large warm-core eddies are rare. According to the numerical estimate of *Watanabe and Hasumi* [2009], the transport of Pacific water (corresponding to ACW) by eddies during August to October when eddy activities are enhanced is 0.2–0.3 Sv. In this case, at most two large warm-core eddies are produced each year. Therefore, the annual transport of excess nitrogenous nutrient by warm-core eddies is less than 20% of that transported by cold-core eddies. Although the annual nitrogenous nutrient transport by warm-core eddies would be much smaller than that by cold-core eddies, warm-core eddies could impact the nutrient distributions in the euphotic zone and hence may influence the phytoplankton distributions in the southwestern Canada Basin.

5. Summary

[14] In late summer/early fall 2010, we found an unusually large warm-core eddy (~100 km in diameter) in the southwestern Canada Basin. The eddy contained ACW with high-ammonium concentrations, and it could supply ammonium to the euphotic zone in the basin, where nitrate was depleted. This may result in ~30% higher biomass of picophytoplankton (<2 μm) over the warm-core eddy compared with that in the surrounding water in the basin. Warm-core eddies are likely major ammonium providers to the euphotic zone in the southwestern Canada Basin, and their role in phytoplankton growth seems to be more important than before because the recent deepening of the nutricline in the

Canada Basin has decreased the nutrient supply to the euphotic zone.

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